Geoacoustic Inversion Using Vertical Line Array Data

Evan K. Westwood, Tracianne B. Neilsen
Applied Research Laboratories
The University of Texas at Austin
Austin, TX 78713-8029
phone: (512) 835-3454 Fax: (512) 835-3258
email: westwood@arlut.utexas.edu, neilsen@arlut.utexas.edu

Award Number: N00014-98-1-0116

Thrust Category: Shallow-Water Acoustics

LONG-TERM GOAL

The long-term goal of this work is to develop a method to extract depth-dependent normal modes and to invert for the acoustic parameters of the ocean and ocean bottom using acoustic data measured on a vertical line array. Funding from this grant was also used to improve, maintain, and distribute a state-of-the-art acoustic normal mode model.

OBJECTIVES

The objectives of the FY00 work were to apply the mode extraction and geoacoustic inversion techniques developed in previous years under ONR funding to measured data and evaluate the strengths and limitations of the methods.

APPROACH

The technical approach for the geoacoustic inversion method being investigated is (1) to use measured data on a vertical line array (VLA) to extract the depth-dependent mode functions of the environment, and (2) to invert for the environmental parameters by using a non-linear least squares technique for finding the best match between extracted and modeled mode functions. The approach for evaluating the usefulness of the method is to apply the method to the ACT-II data measured in the Hudson Canyon area. This work was carried out by Tracianne Neilsen as her Ph.D. dissertation topic in the Physics Department at the University of Texas at Austin, under the supervision of Evan Westwood. A more detailed description of the technical approach is given below.

The required experimental set-up for the mode extraction method consists of a source of opportunity moving in the vicinity of a VLA. The time-dependent, single-frequency pressure field measured on the VLA may be viewed as a matrix of pressures versus receiver depth and source-receiver range. A singular value decomposition (SVD) is performed on the pressure matrix. Under certain conditions, it may be shown, using the standard normal mode expression for the pressure field, that the resulting eigenvectors correspond to the depth-dependent normal mode functions of the waveguide. We refer to this procedure as mode extraction.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Geoacoustic Inversion Using Vertical Line Array Data**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Applied Research Laboratories,The University of Texas at Austin,,Austin,,TX,78713**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

The experimental requirements for the mode extraction to work well are that the water column must be sampled sufficiently well by the receivers of the VLA and that the source must cover a sufficiently large range extent. These requirements allow the pressure matrix to be written as the product of three matrices that have the same properties as the matrices returned by the SVD. An SVD of the pressure matrix yields singular vectors and singular values. The singular vectors span the space of the pressure matrix and, if the mode extraction is successful, correspond to the depth-dependent mode functions. The resulting singular values, which are returned from largest to smallest, are proportional to the modal source excitations. Thus, the source depth chiefly determines the order in which the normal modes will be extracted. The main concern with the singular values is that when neighboring singular values are nearly equal, their corresponding singular vectors are not unique. In this case, the correct mode functions are linear combinations of the eigenvectors, which preserve the orthonormality condition. Modes having close singular values must be ignored in the inversion. Once the mode functions have been extracted from the data, they may be used to invert for the parameters of the acoustic waveguide. The inversion method we used is based on Levenberg-Marquardt nonlinear optimization. In this method, the environmental parameters are adjusted to minimize the squared difference between the extracted mode functions and the corresponding mode functions modeled by the ORCA normal mode model.1 Multiple frequencies are used in order to increase the amount of information contained in the inversion.

WORK COMPLETED

Software that performs the mode extraction and geoacoustic inversion was tested using data measured during the ACT-II experiment. The methods and results are described in detail in the Ph.D. dissertation completed by Tracianne Neilsen. Results have been presented to the underwater acoustics community at three Acoustical Society of America meetings.2,3,4

RESULTS

The mode extraction technique was applied to data measured during the ACT-II experiment. Figure 1 shows the geometry of the ACT-II VLA, one of the measured sound speed profiles, the bottom profile

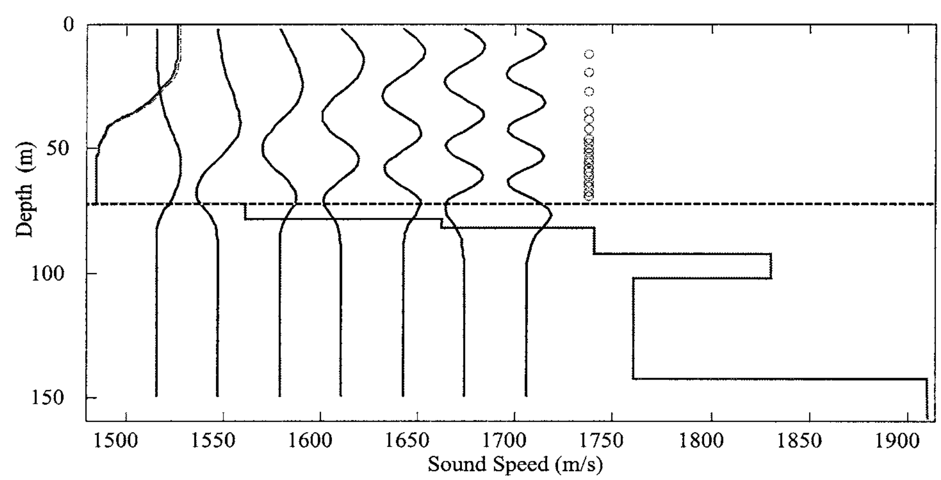

Figure 1. VLA elements (green circles), sound speed profile (red), nominal bottom profile[5] (red), and mode functions (blue) for the ACT-II experiment.

derived in the area from Ref. 5, and the mode functions for the waveguide at 150 Hz. The sparseness of the VLA in the upper part of the water column is not ideal, but simulations indicated that low-order modes could be extracted fairly well.

Mode extraction from the ACT-II data was performed for various range extents for six tones from 100–500 Hz. The mode extraction initially worked better for the lower frequencies (100, 150 and 200 Hz) because the SVD eigenvalues were well separated and because the SNR was high. To obtain good mode extraction results at the higher frequencies (300, 400, and 500 Hz), a larger integration time was used to increase the SNR. Extracted modes at (a) 150 and (b) 300 Hz for a range-independent leg of the TL2/93 run are shown in Fig. 2. The range extent traversed by the source was approximately of 6–14 km. Despite the sparseness of the VLA, the mode extractions appear to have worked very well. The downward-refracting sound speed profile present during the measurements is reflected by the shapes of the extracted mode functions, particularly those of low order. The order of the extracted modes is caused primarily by the modal source excitations at the source depth of 36 m.

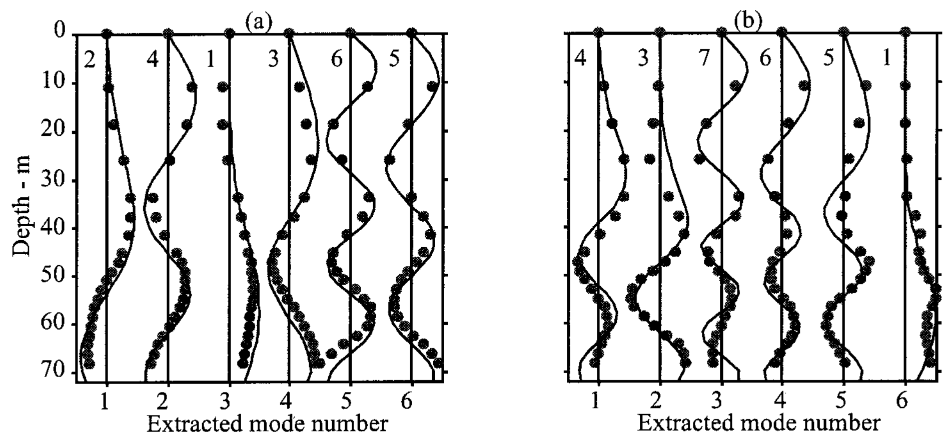

Figure 2. Extracted modes (circles) at (a) 150 Hz and (b) 300 Hz from a range-dependent leg of ACT-II experiment using a range extent of 6-14 km. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig.1 . The numbers near the top of the modes indicate the modeled mode number.

Next, the idea reported in Refs. 6 and 7 that the mode extraction can be performed using a broad distribution of uncorrelated sources was tested using ambient ocean noise recorded during the ACT-II experiment. Specifically, we used 10 minutes of data recorded when the ship was at least 22 km from the VLA and the source for the tones was off. A shorter integration time was used such that the data were averaged over 6.4 Hz frequency bands. The results of mode extraction at (a) 175 and (b) 325 Hz are shown in Fig. 3. The order of the extracted modes gives an approximate value for the effective source depth of the ambient noise. The primary extracted modes all have larger amplitudes at depths less than 10 m than the secondary extracted modes. Thus, the approximate source depth for the ambient noise obtained from the mode extraction is 10 m or less. A shallow depth for the ambient noise is logical because the data was most likely associated with ship or surface noise.

Finally, the mode functions extracted from the six tones were used to invert for the water depth and the geoacoustic parameters of the bottom. The bottom was assumed to consist of two layers and a lower half-space; the layer parameters allowed to vary were the thicknesses, the compressional-wave sound

speeds, the attenuations, and the densities. Inversion runs were performed using modes extracted from various range extents and using different initial environments. The mean and standard deviations s of the results of these inversion runs are summarized in Table 1. The result for the water depth agrees well with the historic values found in Refs. 5, 8, and 9. The presence of a thin top sediment layer and the sound speed at the top of that layer also agree with the historic values. The extracted modes are not sensitive enough to changes in density, attenuation or to any parameters in the second layer to give reasonable estimates of those values.

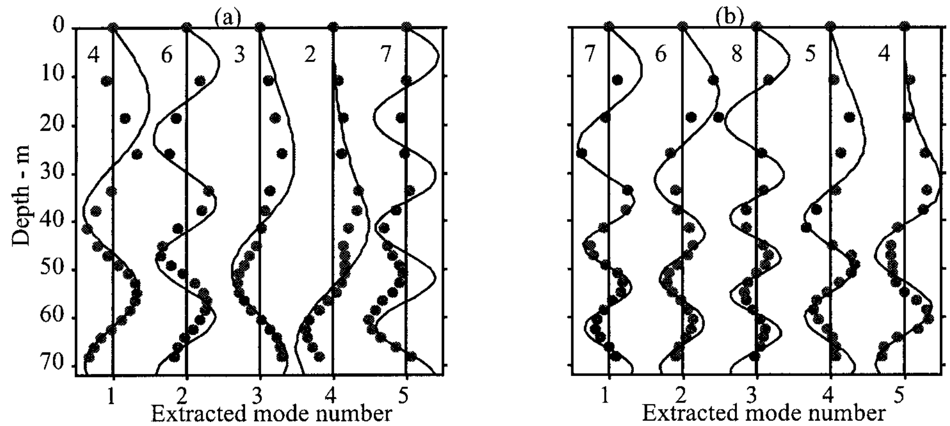

Figure 3. Extracted modes (circles) at (a) 175 Hz from ambient noise recorded during the ACT-II experiment. The continuous lines are modes modeled by ORCA for the nominal environment illustrated in Fig. 1. The numbers near the top of the modes indicate the modeled mode number.

Table 1: Summary of inversion results using data-extracted modes and historic values[5,8,9]

Parameter	Mean	σ	Historic	Units
Water depth	72.35	0.6	71.6 - 73	m
Layer 1: h	5.5	3.3	5	m
c_p (top)	1565	80	1561	m/s
ρ	2.6	0.88	1.86	g/cm^3
α	0.10	0.15	0.053	dB/m-kHz
c_p (bottom)	1675	237	1561	m/s
Layer 2: h	30	20	5	m
c_p (top)	1964	263	1661	m/s
ρ	1.14	0.88	1.96	g/cm^3
α	0.47	0.26	0.082	dB/m-kHz
c_p (bottom)	1984	258	1661	m/s

In summary, the mode extraction technique works well if the VLA samples the water column well and the sources either cover a sufficient range extent or are uncorrelated, as in the case of ambient noise. The acoustic source need not be controlled: its depth, the phase of its tonals, and its precise track do not need to be known. When applied to the ACT-II data set, the mode extraction appears to have worked very well, despite the relative sparseness of the array near the top of the water column. When

the extracted modes were used to invert for the bottom, the results were encouraging, but the depth to which the parameter values could be reliably obtained was less than 10 m. Since the mode functions decay rapidly with depth in the bottom, little information about the bottom below a few wavelengths is available. Although more information would be desirable, the field from sources beyond the near field is only dependent on the parameters near the surface. Unfortunately, the mode functions are not very sensitive to attenuation, even in the top sediment layer. The extracted depth-dependent mode functions are also useful for determining water depth and the sound speed profile in the water column, but in practice these values can usually be measured by other means.

IMPACT/APPLICATIONS

The technique for mode extraction and inversion is applicable to vertical line arrays that span and sample the water column sufficiently well to account for the dominant modes of propagation.

TRANSITIONS

No transitions have occurred for the geoacoustic inversion method. We continue to make the ORCA normal mode model available to the community and to provide support to users when needed. We have been informed of use of the model at the following institutions: NRaD, MPL; NAWC, U. of Hawaii; SACLANT; NRL SSC; U. of Victoria; MIT/WHOI; University of Bochum (Germany); and Pennsylvania State University. ORCA continues to be used as the "mode engine" for a the Range-Dependent Active (RDA) model, an adiabatic-mode modeling tool developed by ARL:UT to provide TL and active sonar predictions in real-world environments.

RELATED PROJECTS

None.

REFERENCES

1. E. K. Westwood, C. T. Tindle, and N. R. Chapman, "A normal mode model for acousto-elastic ocean environments," J. Acoust. Soc. Am., 100, 3631-3645 (1996).

2. T. B. Neilsen and E. K. Westwood, "Mode function extraction from a VLA using singular value decomposition," J. Acoust. Soc. Am. 101, 3025 (1997).

3. T. B. Neilsen and E. K. Westwood, "Environmental inversion using the SVD modes of multiple frequency VLA data," J. Acoust. Soc. Am. 104, 1741 (1998).

4. T. B. Neilsen and E. K. Westwood, "Results of environment inversion using modes extracted from vertical line array data," J. Acoust. Soc. Am. 106, 2133 (1999).

5. M. V. Trevorrow and T. Yamamoto, "Summary of marine sedimentary shear modulus and acoustic speed profile results using a gravity wave inversion technique," J. Acoust. Soc. Amer., 90, 441-455 (1991).

6. P. Hursky, W. S. Hodgkiss, W. A. Kupperman, "Extracting modal structure from vertical array ambient noise data in shallow water," J. Acoust. Soc. Amer., 98, 2971 (1995).

7. P. Hursky, W. S. Hodgkiss, W. A. Kupperman, “Matched field processing with data-derived replicas,” submitted for publication (1999).

8. S. D. Rajan, J. A. Doutt, and W. M. Carey, “Inversion for the compressional wave speed profile of the bottom from synthetic aperture experiments conducted in the Hudson Canyon area,” IEEE J. Oceanic Eng. 23, 174-187 (1998).

9. D. P. Knobles, E. K. Westwood, and J. E. LeMond, “Modal time-series structure in a shallow water environment,” IEEE J. Oceanic Eng., 23, 188-202 (1998).

PUBLICATIONS

T. B. Neilsen, “Normal mode extraction and environmental inversion from underwater acoustic data,” Ph.D. dissertation, The University of Texas at Austin, May 2000.